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(54) **Energy detector**

(57) An energy detector has at least one longitudinal scintillation element (14a). At least two photodiodes (16a-1, 16a-2) are longitudinally disposed over the element. The element can have at least two subelements (14a-1, 14a-2) disposed adjacent each other and aligned in the energy beam direction (12). The subelements can be of the same length or different lengths and photodiodes are disposed over each subelement. The subelements detect different energy levels of an incident energy beam.

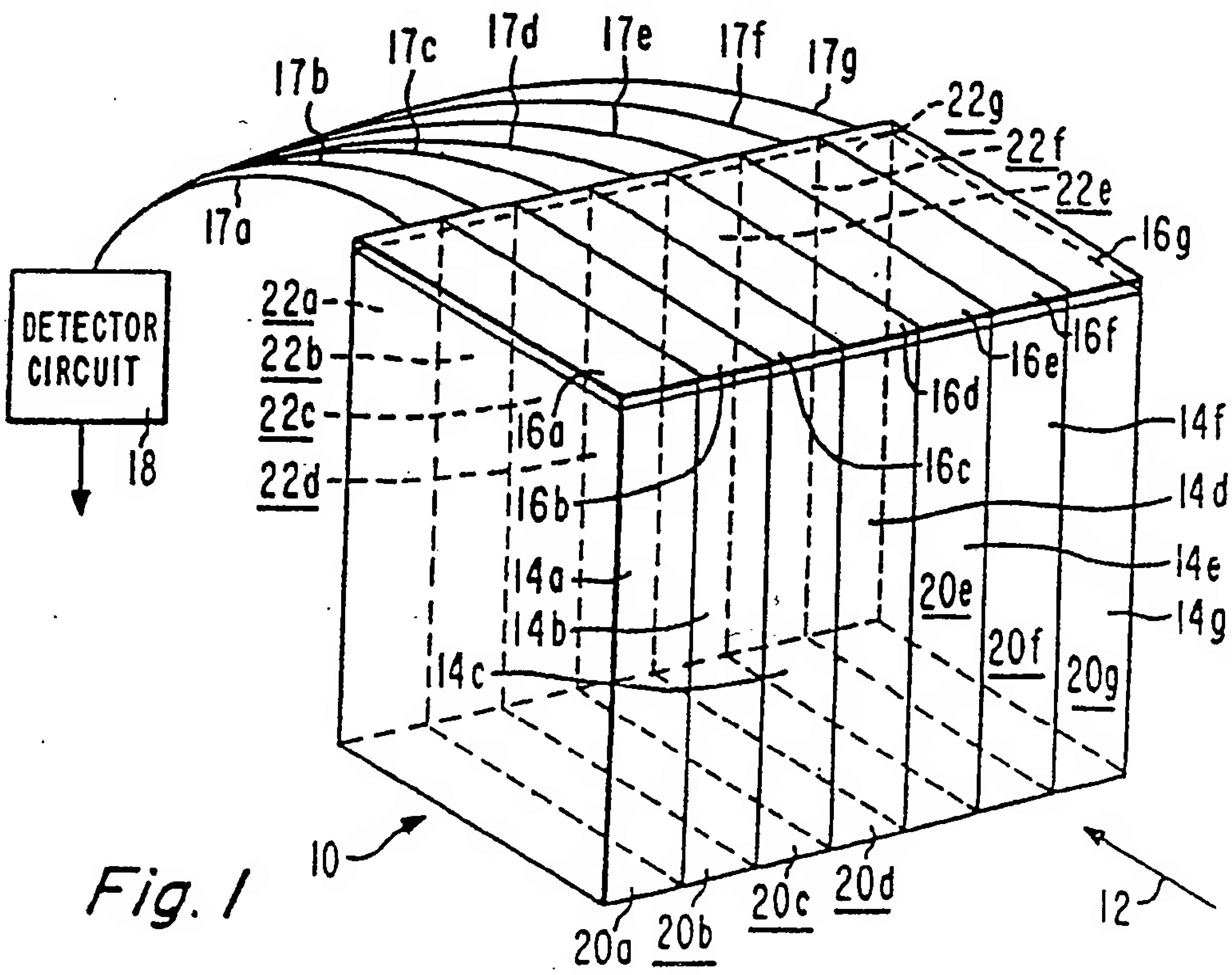

Fig. 1

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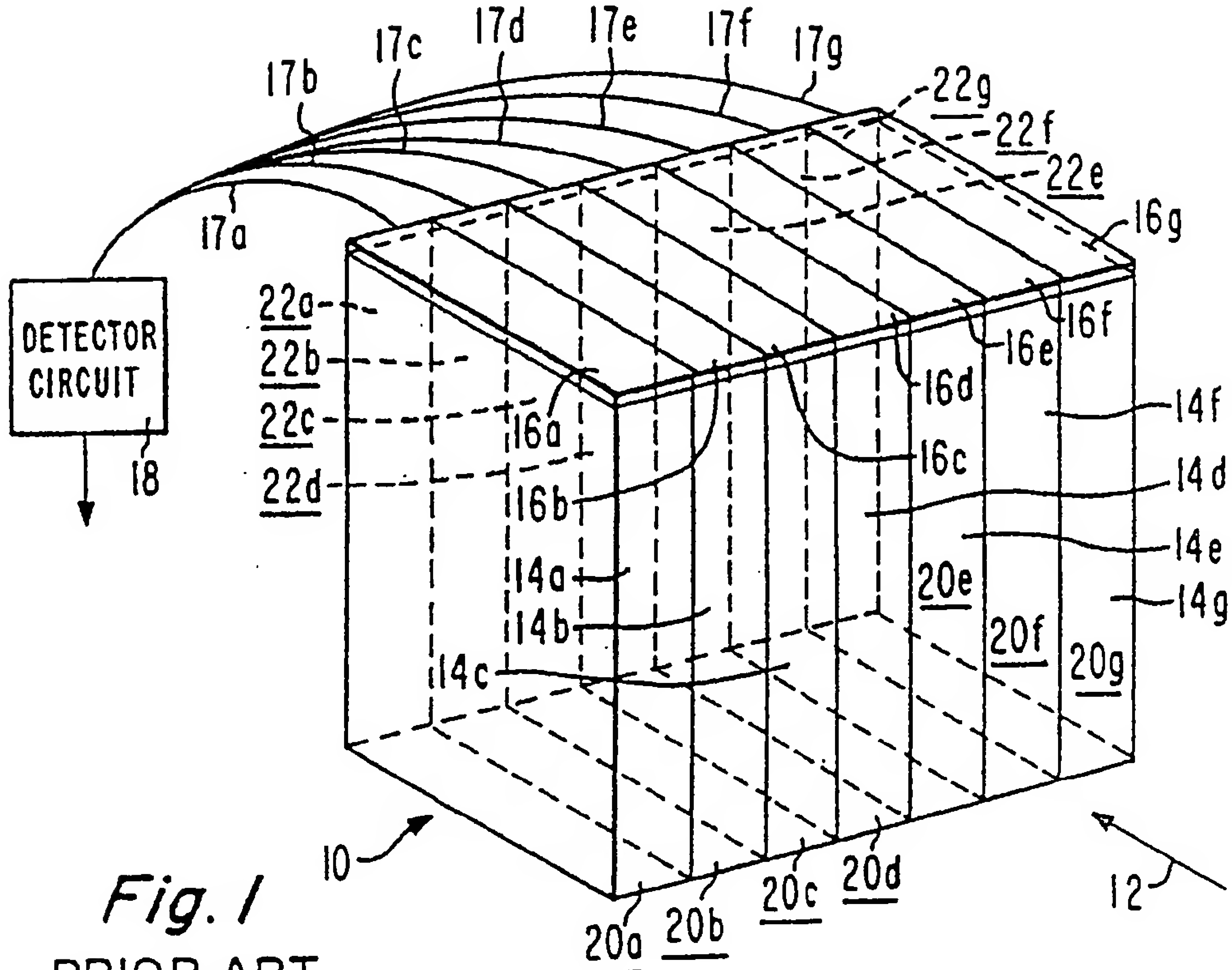

Fig. 1
PRIOR ART

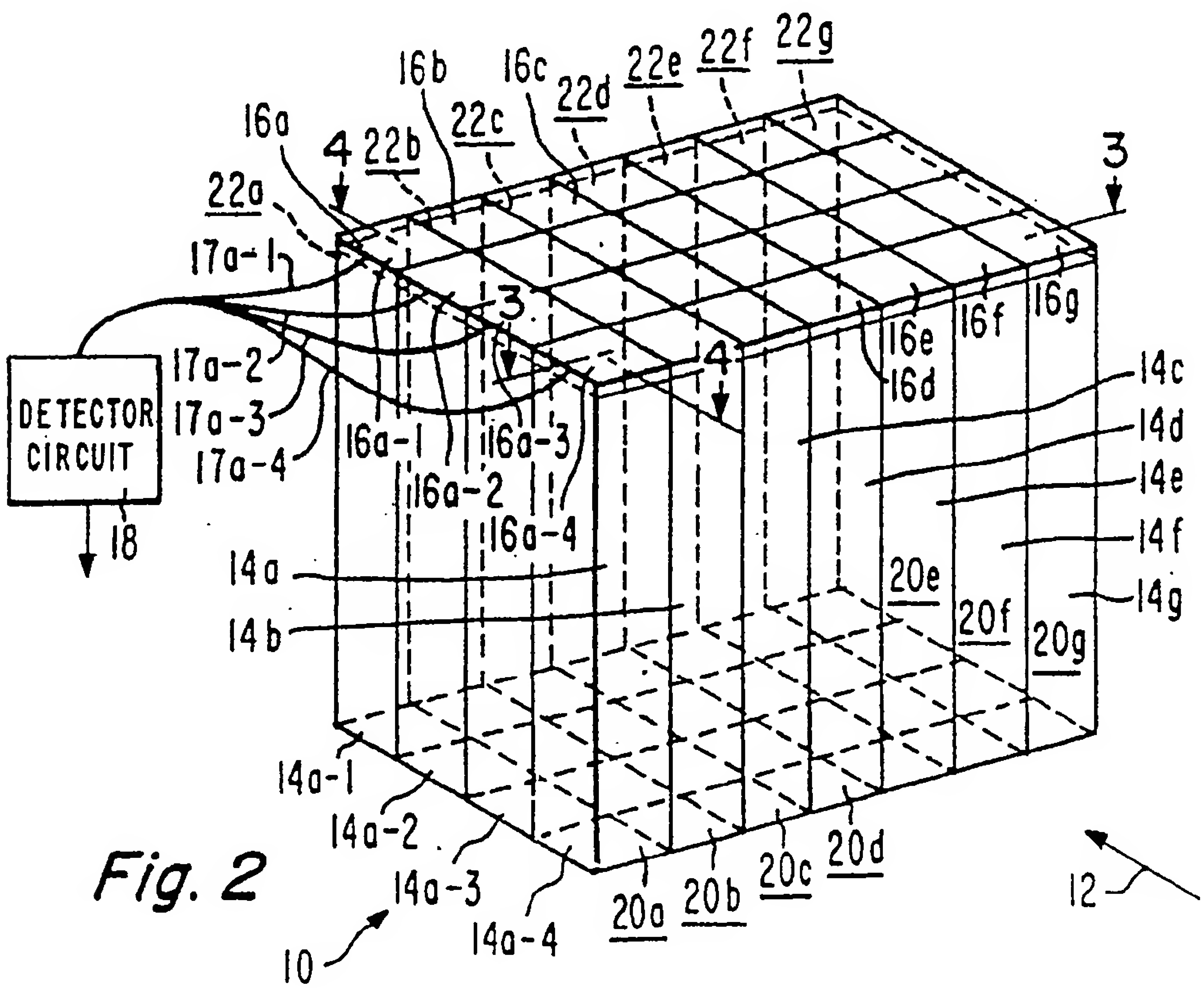

Fig. 2

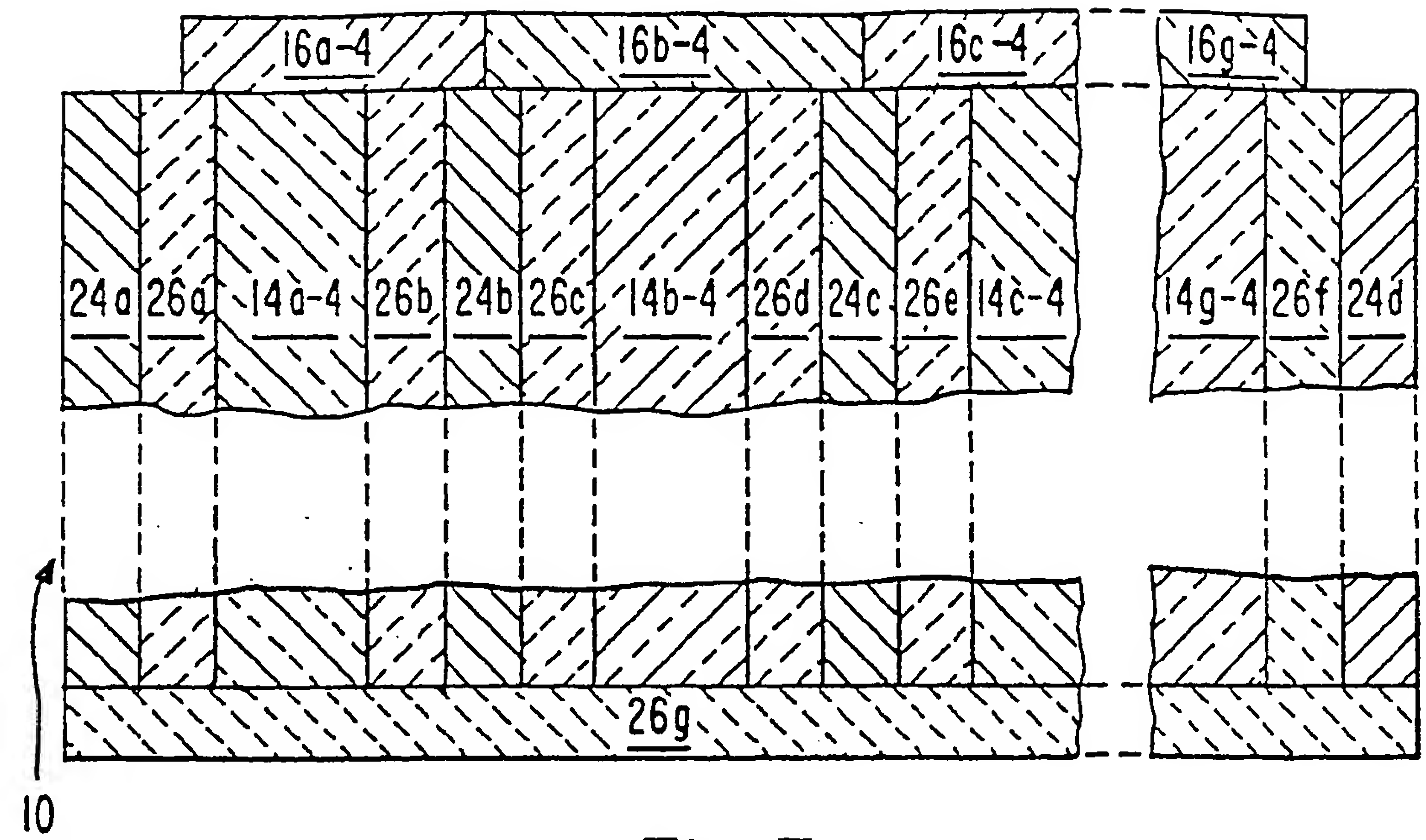
16a-4
16b-4
16c-4
16g-4
24a
26a
14a-4
26b
24b
26c
14b-4
26d
24c
26e
14c-4
14g-4
26f
24d
26g
10

Fig. 3

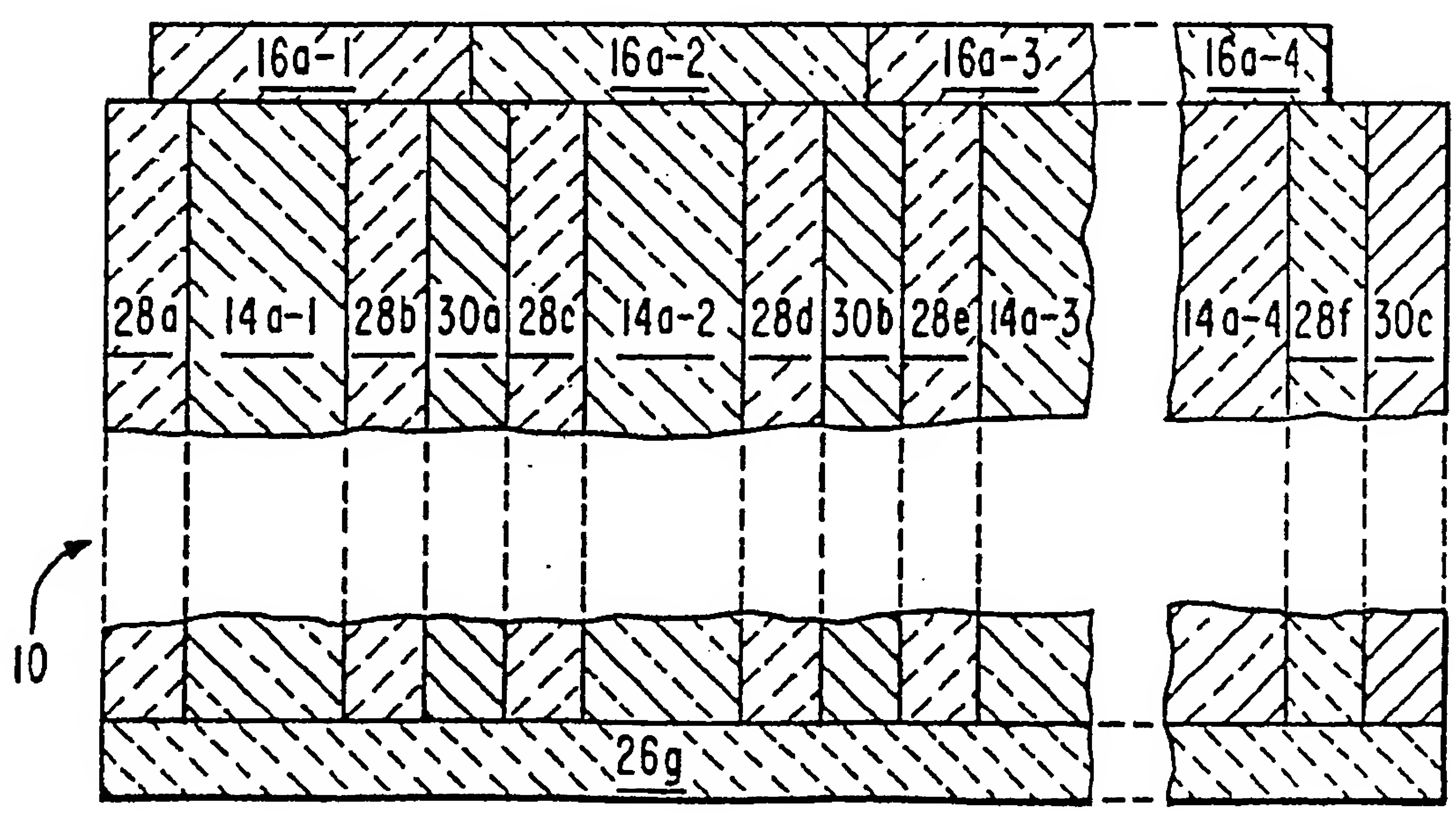
16a-1
16a-2
16a-3
16a-4
28a
14a-1
28b
30a
28c
14a-2
28d
30b
28e
14a-3
14a-4
28f
30c
26g
10

Fig. 4

ENERGY DETECTOR

The present invention relates to an energy detector, for example, an X-ray detector for use in an imaging system.

Present day X-ray inspection systems provide images of an X-ray linear attenuation coefficient. Such images are very useful for detecting anomalies, but they are limited in the total amount of information they provide about the object, since the image represents an average value of attenuation coefficient over the spectrum of energies produced in a typical X-ray tube source. Imaging at multiple energies (spectroscopic imaging) has the potential to provide a great deal more information about the object under investigation, including chemical composition and density of the object. These are new non-destructive evaluation (NDE) capabilities which have not been available to date. The problem, however, is that such multiple energy imaging has not been feasible due to the lack of energy sensitive detectors which can handle the high X-ray fluxes associated with modern imaging systems.

In particular, current X-ray detectors can generally be divided into two categories: counting detectors and integration detectors. Counting detectors can provide energy spectral information, but their count rates are generally not sufficient for the high X-ray fluxes required in modern imaging applications. Integration detectors can handle high fluxes, but they do not provide energy discrimination.

Dual energy scanning has been used to provide element identification capabilities. State of the art dual energy scanning systems therefore use integration detectors and scan the part twice at two separate energies. For example, ARACOR (J.H. Stanley & J.J. LePage, "A New Radiographic Corrosion Inspection Capability", AFWAL Report TR-85-4130, January 1986) has developed a system, using a scintillation detector, for detecting corrosion in metals which scans the object

first at 420 KVP (kilovolts peak) and next at 250 KVP with an industrial X-ray tube to provide the two images. Chemical element discrimination between adjacent elements in the periodic chart is claimed to be possible with this system. The main problem with this approach is the time, dose, and alignment issues related to the two scans required. In addition, images are recorded at only two energies, so this technique is not a true spectroscopic imaging method.

In order to better understand the present invention, a conventional multi-element solid state X-ray integration detector 10 is shown in Figure 1. Detector 10 detects incident energy beam 12, e.g., X-rays, beta rays, etc., and comprises a scintillator having plurality of rectangular (or otherwise shaped) slab scintillation elements 14a, 14b, 14c, 14d, 14e, 14f, and 14g. Although seven elements 14 are shown, as few as one and as many as desired can be used. Usually, it is desirable to divide detector 10 into several elements since the incident beam 12 when stopped will generate a conical shaped scintillation light beam. If only one element having more than one sensing means (described below) is used, sections of the conical light beam can enter adjacent sensing elements and lower spatial resolution results compared to the case where a plurality of elements are used. Elements 14 are are disposed laterally (perpendicular to the direction of beam 12) adjacent each other and are separated by certain collimating and reflection layers (not shown in Fig. 1 but described below). The dimensions of elements 14 are not critical and can be from a few mils in width (the lateral direction) to several millimeters. Elements 14 respectively have front entry faces 20a, 20b, 20c, 20d, 20e, 20f, 20g and rear faces 22a, 22b,22c, 22e, 22f, and 22g. Front faces 20 are respectively longitudinally (in the direction of beam 12) disposed with respect to rear faces 22. Respectively disposed on top of elements 14 are a plurality of optical sensing means 16a, 16b, 16c,

16d, 16e, 16f and 16g, e.g., photodiodes, that are respectively coupled to a detector circuit 18, e.g., amplifiers (not shown), for each of the sensing means 16 by means of connections 17a, 17b, 17c, 17d, 17e, 17f, and 17g. The output of circuit 18 is then applied to signal processing and image reconstruction circuits (not shown).

In operation, an X-ray source (not shown) generates X-rays that pass through an object to be imaged (not shown). The resulting transmitted X-rays are shown as incident X-rays 12 in Figure 1. Beam 12 is incident upon front faces 20 and then enters elements 14 where it causes scintillation that is detected by sensing means 16. The output signal from means 16 is then amplified by circuit 18. The detector provides high flux detection capability and relatively high quantum efficiency. It does not, however, provide energy discrimination capability.

It is therefore an object of the present invention to provide a detector for multiple energies that can detect high fluxes and does not require multiple scans.

One aspect of the invention provides a multiple energy detector of energy incident in a longitudinal direction comprising a scintillator having at least one longitudinal scintillation element, said element having a front entry face and a rear face disposed in said longitudinal direction, said entry face being adapted to receive the incident energy; and an optical sensing means having at least one element, said sensing means element having a plurality of subelements disposed adjacent each other in the longitudinal direction and adjacent to said scintillation element.

The detector may be arranged to detect X-rays or Beta-rays.

In the drawings:

Figure 1 is an isometric view of a prior art scintillation detector;

Figure 2 is an isometric view of a detector in accordance with the invention;

Fig. 3 is a front cross-sectional view taken along line 3-3 of Fig. 2; and

Fig. 4 is a side cross-sectional view taken along line 4-4 of Fig. 2.

In the drawing identical reference numerals are given to corresponding elements.

Figure 2 shows that in detector 10 in accordance with the invention, sensing means element 16a comprises four subelements 16a-1, 16a-2, 16a-3, and 16a-4, e.g., PN or PIN photodiodes, pixels of a charge coupled device (CCD) imager, etc., disposed adjacent each other in the longitudinal direction. Sensing means 16a has a number of subelements equal to the number of energies of beam 12 it is desired to measure. In general, sensing means 16a has at least two subelements in order to measure at least two energies in beam 12. Individual conductors 17a-1, 17a-2, 17a-3, and 17a-4, respectively connect subelements 16a-1, 16a-2, 16a-3, and 16a-4, to circuit 18. Similarly, sensing means 16b, 16c, 16d, 16e, 16f, and 16g also each comprise subelements (not numbered for the sake of clarity) that are normally equal in number to the number of subelements of element 16a. Also each of the subelements of sensing means elements 16b, 16d, 16e, 16f, and 16g have an individual connection (not shown for the sake of clarity) to detector circuit 18. In circuit 18 there are individual channels (not shown) for all of the subelements of sensing means 16.

Also similarly, scintillation element 14a comprises subelements 14a-1, 14a-2, 14a-3, and 14a-4, disposed adjacent each other in the longitudinal direction and each have sensing means 16a subelements 16a-1, 16a-2, 16a-3, and 16a-4, respectively disposed on the top thereof. In like manner, scintillation elements 14b, 14c 14d, 14e, 14f, and 14g, each have a plurality of subelements (not numbered for the sake of clarity) with corresponding subelements of sensing means 16b, 16c,

16d, 16e, 16f, and 16g, respectively disposed at the top thereof.

While the above described embodiment shows that the subelements of scintillation element 14a are equal in number to the sensing means subelements 16a, and the same for the subelements of the remaining scintillation elements and their respective sensing means subelements, this is not required. In particular, for a given scintillation element there can be less scintillation subelements than there are sensing means subelements, or even no scintillation subelements at all. However, with a lower number of scintillation subelements, there might occur less clearly defined energy, resolution due to optical crosstalk between the subelements of the respective sensing means element.

At the left of Fig. 3 is a collimating layer 24a, which is next to a reflecting layer 26a. Next is subelement 14a-4, which in turn is next to a reflecting layer 26b. Thereafter is disposed a collimating layer 24b, and then a reflecting layer 26c, which lies adjacent subelement 14b-4. A reflecting layer 26d is disposed on the other side of subelement 14b-4 and then sequentially is a collimating layer 24c, a reflecting layer 26e, and subelement 14c-4. This pattern repeats across the entire front 20 of detector 10 until the last subelement 14g-4, which has next to it a reflecting layer 26f and then a collimating layer 24d. Respectively disposed over subelements 14a-4, 14b-4, 14c-4, ... and 14g-4, are sensing means 16a-4, 16b-4, 16c-4, ... and 16g-4. As known in the art, sensing means 16 can be secured to elements 14 by a glue (not shown), preferably one that matches the index of refraction therebetween. At the bottom of detector 10 is a reflecting layer 26g. If desired, collimating layers 24 can be extended to project in front of front surfaces 20 for yet better collimation. Also, if desired, collimating layers 24 and/or reflecting layers 26a-26f can be eliminated. Also the scintillator could be one

large piece to minimize fabrication difficulties. However spatial resolution will then be lower. Reflecting layer 26g can also be eliminated, but then efficiency will be lower due loss of light from the bottom surface (not numbered). Collimating layers 24 can have a width between about 1/8 to 1/4 mm, while the subelements can have a width between about 25 μm to 3 mm depending upon the application of detector 10. Typically, NDE will have the lower widths, while medical uses will have the larger widths. Reflecting layers 26 can have a width of about 50 μm.

Similarly, Fig. 4 shows sequentially from the left, a reflecting layer 28a, subelement 14a-1, a reflecting layer 28b, an energy filter 30a, a reflecting layer 28c, subelement 14a-2, a reflecting layer 28d, an energy filter 30b, a reflecting layer 28e, etc., until there is subelement 14a-4, a reflecting layer 28f, and an energy filter 30c. As above, reflecting layers 28 and/or filters 30 can be eliminated; however there then will be lower energy resolution and lower efficiency due to loss of light from the front surfaces 20 and the rear surfaces 22 of elements 14. The thickness of filters 30 can be between about 10 μm to 5 mm, while the thickness of reflecting layers 28 can be about 50 μm. The subelements can have a thickness between about 25 μm to 3 mm.

Collimating layers 24 can be of, e.g., Pb, W, etc. Preferably, reflecting layers 26 and 28 comprises a metal oxide, e.g., TiO_2, secured to elements 14 and its subelements by an epoxy glue binder. TiO_2 is a good choice for layers 26 and 28 since it is white and therefore reflects most colors, and has a diffuse reflection so that the scattered light will be more likely to exit elements 14 and its subelements to sensors 16 and not be absorbed by elements 14 and its subelements. Details about such a coating can be found in U.S. Pat. Nos. 4,560,877 and 4,563,584. In particular, the particles of TiO_2 should

have a size of about the wavelength of the emitted photons (described below). Filter layers 30 can be Pb, Al, Cu, etc.

The scintillation material of elements 14 comprise a sintered rare earth ceramic oxide, such as a Y:Gd X-ray absorber. In particular, elements 14 can comprise between about 20 to 50 mole percent Gd_2O_3, between about one to six mole percent Eu_2O_3, with the remainder Y_2O_3. More particularly, it can comprise about 30 mole percent Gd_2O_3, about three mole percent Eu_2O_3, and about 67 mole percent Y_2O_3. If desired, about 0.02 mole percent Pr_2O_3, can be added as an afterglow reducer. Details about such materials, which are good scintillators, can be found in prior art patents, e.g., U.S. Pat. No. 4,518,546. Such materials are also robust, chemically inert, stable, and micromachinable. They are also substantially transparent to the visible light band because the mixture can be sintered to nearly perfect theoretical density and exhibits cubic crystal structure. This eliminates imperfections and changes in the index of refraction at grain boundaries, both of which cause transparency-reducing optical scattering. Thus elements 14 can be large in the longitudinal (beam 12 direction) for good X-ray absorption without significant loss of optical sensitivity. Other transparent scintillators, e.g., BGdO, which is a good X-ray absorber, might also be used as the material of elements 14. Still other materials, e.g., CsI, $CdWO_4$, BiGe, etc., can be used.

Detector 10 may be supported, for example, by an IC (not shown) that is mounted on a circuit board (not shown). The IC comprises sensing means 16 onto which the scintillator elements 14 are mounted. Alternately, detector 10 may be mounted with adhesive or a fixture (neither shown) to a support device such as a microscope slide (not shown) used at various steps in the manufacture.

In operation, incident beam 12, which is transmitted through the imaged object, normally has a wide range of energies. Some of the low level energy is absorbed by filter 30c. The lowest energy X-rays are

then preferentially absorbed in subelements nearest front faces 20, i.e., those subelements having the suffix "-4". Then some of the next lowest energy is absorbed by filter 30b. The next lowest energy X-rays are then primarily absorbed in the next to front subelements, i.e., those the the suffix "-3", etc. This is an effect called "beam hardening".

The X-rays are primarily absorbed by the Gd atoms in scintillation elements 14. In turn, the Gd Atoms cause the creation of electron-hole pairs that in turn cause the subelements of elements 14 to scintillate, i.e., emit visible light photons. If elements 14 are made of the material described above and also in said patents, they will emit light at a wavelength of 611 μm, which is red, due to the presence of Eu atoms. Since said material is substantially transparent to this wavelength, the photons will be transmitted through elements 14, The photons are reflected by the various reflecting layers and eventually they will be incident on the subelements of sensing means 16. Since the sensing means 16 are preferably made of Si, they are especially sensitive to light of this wavelength and thus provide an electrical signal in response to the incident photons. This signal is then amplified by the amplifiers of circuit 18 and then applied to signal processing and image reconstruction circuits (not shown).

The beam hardening effect described above assures that the lower energy X-rays in the incident beam will be preferentially absorbed near the front of the detector 10, and succeeding detector subelements will be sensitive to successively higher energies. The effect is large. For example, for a Cesium Iodide detector with 5 subelements, successively called S1 - S5 with S1 being at the front, in the beam direction each subelement being 0.1 in (2.54 mm) deep, and some simplifying assumptions about the spectrum from a 420 KVP X-ray tube source, the average energy absorbed in each of the

subelements is S1 - 79.2 keV, S2 - 205.9 keV, S3 - 226.5 keV, S4 - 247.0 keV, and S5 - 264.9 keV.

Perfect energy discrimination is not required for the multiple energy image to be useful. It is sufficient that the average energy absorbed in the subelements of the detector be sufficiently separated. However, energy discrimination can be enhanced by several other techniques as well. First, detector materials or material properties can be varied to change the average pathlength for X-rays of any energy and modify the average energy deposited in the subelements of the detector. Second, the subelement lengths in the beam direction can be varied to change the average energy deposited in each subelement. Third, various beam filters can be placed in front of detector 10 and used to tailor the incident beam spectrum and again modify the average energy detected in the various subelements of the detector. These options provide substantial flexibility and allow tailoring of the response of the individual subelements to almost any functional form.

This embodiment for multiple energy detection has many advantages. First, it allows simultaneous acquisition of the data at all energies of interest, so no dose or time penalty is required to achieve both images. Second, it uses the detector material itself, i.e., the scintillator, to provide energy discrimination, so there is no risk of detector contamination with foreign materials. Third it is possible to add the signals from the subelements together before image reconstruction, so normal imaging is possible.

The multiple energy imaging technique is useful over a wide range of energies. It can be restricted to a dual energy technique, i.e., only two subelements of sensing means 16 for each element 14, each element 14 having none or two subelements, and applied to the case where the X-ray linear attenuation coefficient is made of photoelectric component and a Compton component

to provide chemical element identification. It can also be used at lower energies where imaging above and below a characteristic X-ray line of a given element can provide chemical element discrimination. The new detector provides both a true materials characterization tool and non-distructive evaluation tool in one unit.

It will be appreciated that many other embodiments are possible within the spirit and scope of the invention.

CLAIMS:

1. A multiple energy detector of energy incident in a longitudinal direction, said detector comprising:

a scintillator having at least one longitudinal scintillation element, said element having a front entry face and a rear face disposed in said longitudinal direction, said entry face being adapted to receive the incident energy; and

an optical sensing means having at least one element, said sensing means element having a plurality of subelements disposed adjacent each other in the longitudinal direction and adjacent to said scintillation element.

2. The detector of Claim 1 wherein said energy comprises X-rays.

3. The detector of Claim 1 wherein said energy comprises beta rays.

4. The detector of Claim 1, 2 or 3 wherein said subelements are of equal length.

5. The detector of Claim 1, 2, 3 or 4 wherein said scintillation element comprises a plurality of subelements disposed adjacent each other in the longitudinal direction.

6. The detector of Claim 5 wherein said scintillation subelements are equal in number to said sensing means subelements, said sensing means being respectively disposed adjacent said scintillation subelements.

7. The detector of Claim 5 or 6 further comprising reflecting layers disposed on said scintillation subelements, and energy beam filters disposed between said scintillation subelements.

8. The detector of claim 7 wherein said reflecting layers comprise TiO_2 and said filters comprise Cu, Al, or Pb.

9. The detector of Claim 7 or 8 wherein said reflecting layers have a thickness of about 50 μm, said filters have a thickness between about 10 μm to 5 mm,

and said scintillation subelements have a thickness between about 25 μm to 3 mm.

10. The detector of claim 5, 6, 7, 8 or 9 wherein both of said pluralities are two in number.

11. The detector of any preceding claim wherein said scintillator further comprises a plurality of scintillation elements laterally disposed with respect to each other, said sensing means further comprising a plurality of elements respectively disposed adjacent said scintillation elements.

12. The detector of Claim 11 further comprising reflecting layers disposed on said scintillation elements, and collimating layers disposed between said scintillation elements.

13. The detector of claim 12 wherein said reflecting layers comprise TiO_2 and said collimating layers comprise Pb or W.

14. The detector of claim 12 wherein said reflecting layers have a width of about 50 μm, said collimating layers have a width between about 1/8 to 1/4 mm, and said scintillaition elements have a width between about 25 μm to 3 mm.

15. The detector of any preceding claim wherein said scintillator comprises between about 20 to 50 mole percent Gd_2O_3, between about one to six mole percent Eu_2O_3, with the remainder Y_2O_3.

16. The detector of claim 15 wherein said scintillator comprises about 30 mole percent Gd_2O_3, about three mole percent Eu_2O_3, and about 67 mole percent Y_2O_3.

17. The detector of claim 16 wherein said scintillator further comprises about 0.02 percent Pr_2O_3.

18. The detector of any one of claims 1 to 14 wherein said scintillator is BGdO, CsI. CdWO or BiGe.

19. The detector of claim 5 or any claim dependent thereon wherein said scintillator subelements are rectangular in shape.

20. The detector of any preceding claim wherein said sensing means subelements each comprise CCD pixels.

21. An energy detector substantially as hereinbefore described with reference to Figures 2 to 4.

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